Final Report
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Manipulation and Control of Nanometer-scale Magnetism for Multifunctional Information Processing

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RESEARCH ACCOMPLISHMENTS

• *Spontaneous Spin Polarization in Hybrid FM/Semiconductor Structures*

We discovered that photoexcited electrons in an n-GaAs epilayer rapidly (< 20 ps) spin-polarize due to the proximity of an epitaxial ferromagnetic metal. Using pump-probe spectroscopy, investigations of the coherent spin dynamics of these electrons yield long spin coherence lifetimes (~4 ns) and spin polarization comparable in magnitude to traditional optical spin injection. Comparison between Fe/GaAs and MnAs/GaAs structures shows that the electron spins align parallel and antiparallel to the magnetizations, respectively. In addition, the GaAs nuclear spins are dynamically polarized with a sign determined by the spontaneous electron spin orientation. In Fe/GaAs, competition between nuclear hyperfine and applied magnetic fields results in complete quenching of electron spin precession. A series of angle-dependent studies have shown that this new effect arises from either scattering from the ferromagnetic epilayer, or possibly from rapid carrier tunneling between the two systems. Optically-induced electrons rapidly spin polarize, and subsequently polarize the nuclear lattice. The hybrid systems have been shown to be a source of non-volatile coherent electrons, and can be generated using incoherent light (one photon in = one spin-polarized electron out) and flipped (controlled) with the adjacent ferromagnetic layer.

• *Ferromagnetic Imprinting of Nuclear Spins in Semiconductors*

Optically-generated electron spins in semiconductors show remarkable resilience against environmental decoherence, making it possible to envision a new class of magnetoelectronics based on the coherent superposition of quantum spin states. To examine how a ferromagnetic layer may be used to control coherent electron spins in a neighboring GaAs semiconductor, we fabricated a series of insulating and doped hybrid magnetic/GaAs structures using the following ferromagnets: (Ga,Mn)As, MnAs, digital (Ga,Mn)As, and a single layer of Mn delta-doping. Ultrafast optical pump-probe measurements on these samples reveal that the dynamics of coherent electron spins in the GaAs layer are strongly affected by the ferromagnet, but not through fringe fields or direct exchange interactions. Unexpectedly, the ferromagnet causes nuclear spins in the GaAs layer to become hyperpolarized (~25%) and align with the magnetization. These polarized nuclei, in turn, generate large effective magnetic fields on the coherent electron spins through the hyperfine interaction—as high as 15000 G in small external fields (< 1000 G)—thereby leading to electron spin precession in the GaAs layer that is dominated by interactions with nuclei. Thus, ferromagnetic control of electron spin coherence is achieved by 'imprinting' nuclear spins in the GaAs layer.

• *Spatial Imaging of Magnetically Patterned Nuclear Spins in GaAs Devices*

We exploited ferromagnetic imprinting to create complex laterally defined regions of nuclear spin polarization in lithographically patterned MnAs/GaAs epilayers grown by molecular beam epitaxy (MBE). In particular, we investigated how closely the nuclear polarization in the GaAs tracks the magnetization of patterned ferromagnet structures using a recently constructed low temperature time-resolved Kerr microscope (TRKM) with ~1 μm resolution. We found that the spatial variation of the GaAs nuclear polarization approximates the shape of the patterned ferromagnet, with a transition from maximum to zero nuclear polarization occurring over a distance of ~10 μm, yielding effective magnetic field gradients of $\sim 10^4$ T/m at T = 5K. We also find that this gradient remains roughly constant with increasing temperature, in contrast to the electronic mobility. This suggests that the longitudinal electron spin lifetime may play a role in setting the transition width. Finally, we observe a monotonic decrease in the local gradients with increasing GaAs epilayer thickness as well as fluctuations in the nuclear polarization as a function of lateral position under the ferromagnet. The results reveal a flexible scheme for lateral engineering of spin-dependent energy landscapes in the solid state.

We have also demonstrated direct optical patterning and imaging of spin-polarized nuclear domains in GaAs epilayers. Through the contact hyperfine interaction, these nuclear domains act on electron spins as localized magnetic fields with steep magnetic field gradients, the width of which depend on the thickness of the GaAs epilayer. This ability to pattern the nuclear polarization and its resulting effective fields and field gradients may lead to new concepts for spintronic devices as well as provide an intriguing tool for mesoscopic spin manipulation.

• *Voltage Control of Nuclear Spin in Ferromagnetic Schottky Diodes*

We employed optical pump-probe spectroscopy to investigate the voltage dependence of spontaneous electron and nuclear spin polarizations in hybrid MnAs/n-GaAs and Fe/n-GaAs Schottky diodes. Through the hyperfine interaction, nuclear spin polarization that is imprinted by the ferromagnet acts on conduction electron spins as an effective magnetic field. We demonstrate tuning of this nuclear field from <0.05 to 2.4 kG by varying a small bias voltage across the MnAs device. In addition, a connection is observed between the diode turn-on and the onset of imprinted nuclear polarization, while traditional dynamic nuclear polarization exhibits relatively little voltage dependence.

We investigated the influence of a voltage applied across metallic-ferromagnet/n-GaAs Schottky diodes processed from similar structures. We find that the ferromagnetically imprinted nuclear polarization (termed magnetic DNP henceforth) is strongly voltage dependent, being largest at positive bias while almost completely suppressed under reverse bias. Comparison to the diode electrical characteristics reveals a connection between the current turn-on and onset of magnetic DNP. This is in contrast to traditional optical DNP, i.e. due to an electron spin imbalance generated by polarized optical excitation, which is measured to have relatively weak voltage dependence. Analysis of these results suggests that the observed voltage dependence of magnetic DNP is due to changes in the degree of spontaneous electron spin polarization. The voltage

dependence is consistent with spin-dependent electron scattering at the ferromagnet/GaAs interface. However, the sign of spin polarization does not appear to be set by the Schottky barrier height as predicted, but may be due to another factor such as the ferromagnet's spin-dependent density of states.

• *Giant Planar Hall Effect in (Ga,Mn)As Lateral Devices*

We reported the observation of a giant planar "Hall" effect (GPHE) in epitaxial (Ga,Mn)As thin .1 micron devices. This is manifested as a spontaneous transverse voltage that develops, because of spin-orbit coupling, in response to longitudinal current in the absence of an applied field. Analogous effects studied in metallic ferromagnets, are exceedingly small - typically of order milliohms Related phenomena have recently been investigated in ferromagnetic semiconductors, but here we report the previously unrecognized, and quite remarkable, response of the GPHE to an applied in-plane magnetic field. Within the high quality, single domain ferromagnetic semiconductors investigated here we find a switchable effect that is four orders of magnitude stronger than found in metallic ferromagnets. We performed measurements that take advantage of this strong GPHE to provide insight, and unprecedented resolution, into the mechanism of magnetic switching within these materials. These data, in turn, enable complete characterization of the magnetic anisotropy of the (Ga,Mn)As epilayers. At present, the large magnitude of this PHE is not fully understood. We presume this phenomenon stems from the combined effects of significant spin-orbit coupling in the valence band of the zincblende crystal structure, and the large spin polarization of holes in (Ga,Mn)As. The temperature dependence of the magnetization and the coercivity determined by electrical measurement should provide additional insight into the underlying physical mechanisms.

• *Highly Enhanced Curie Temperature in (Ga,Mn)As Epilayers*

We reported Curie temperatures up to 150 K in annealed $Ga_{1-x}Mn_xAs$ epilayers grown with a relatively low Ga:As beam equivalent pressure ratio. A variety of measurements (magnetization, Hall effect, magnetic circular dichroism and Raman scattering) show that the higher ferromagnetic transition temperature results from an enhanced free hole density. The data also indicate that, in addition to the carrier concentration, the sample thickness limits the maximum attainable Curie temperature in this material – suggesting that the free surface of $Ga_{1-x}Mn_xAs$ epilayers is important in determining their physical properties. This represents a ~50% increase in the transition temperature for this class of ferromagnetic semiconductors.

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INVITED TALKS

Over 100 invited presentations on these research results have been delivered at national and international conferences, as well as university colloquia, during this period.

PATENTS

Two patents have been written based on these results during this award period:

"Bipolar Spin Transistors and Applications of the Same," M. Flatté, Z. Yu, E. Johnston-Halperin, and D. D. Awschalom, Patent pending (2003).

"Giant Planar Hall Effect in Epitaxial (Ga,Mn)As Devices," Inventors, H. Tang, M. Roukes, R. Kawakami, and D. D. Awschalom, Provisional Patent Application No. 60/390,977, filed June 21, 2002.

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2. FERROMAGNETIC IMPRINTING OF NUCLEAR SPINS IN SEMICONDUCTORS
3. SPATIAL IMAGING OF MAGNETICALLY PATTERNED NUCLAR SPINS IN GAAS DEVICES
4. VOLTAGE CONTROL OF NUCLEAR SPIN IN FERROMGNETIC SCHOTTKY DIODES
5. GIANT PLANAR HALL EFFECT IN (GA,MN) AS LATERAL DEVICES
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